The Boundary Layer Growth in an Urban Area

D. Pino [a,1] J. Vilà-Guerau de Arellano [b] A. Comerón [c] F. Rocadenbosch [c]

[a] *Institute for Space Studies of Catalonia (IEEC/CSIC), E-08034 Barcelona, Spain*

[b] *Department of Meteorology and Air Quality, Wageningen University, 6701 AP Wageningen, The Netherlands*

[c] *Department of Signal Theory and Communications, Technical University of Catalonia, E-08034 Barcelona, Spain*

Abstract

The development and maintenance of the atmospheric boundary layer (ABL) plays a key role in the distribution of atmospheric constituents, specially in a polluted urban area. In particular, the atmospheric boundary layer has a direct impact on the concentration and transformation of pollutants. In this work, in order to analyze the different mechanisms which control the boundary layer growth, we have simulated by means of the non-hydrostatic model MM5 several boundary layer observed in the city of Barcelona (Spain). Sensitivity analysis of the modeled ABL are carried out by using various descriptions of the planetary boundary layer. Direct and continuous measurements of the boundary layer depth taken by a lidar are used to evaluate the results obtained by the model.

Key words: mesoscale models, boundary layer depth, lidar observations, air pollution

1 Introduction

The accuracy of air-quality models (AQMs) depends on the correct calculation of physical and chemical variables. It is clear that the meteorological fields

Email address: pino@ieec.fcr.es (D. Pino).

[1] Partially supported by project IMMPACTE (CIRIT, DME, Spain)

supplied to AQMs may contain uncertainties which adversely affect model simulations. Mesoscale weather-forecast models are usually used to supply these meteorological fields to AQMs. The principal meteorological variables needed for AQMs, among others, are horizontal and vertical wind components, water vapor mixing ratio, precipitation, surface fluxes and boundary layer depth. The majority of these variables change rapidly in the atmospheric boundary layer. In this research, we focus on the growth of the boundary layer.

It is well known that the forcing which drives the evolution of the atmospheric boundary layer are the heat and moisture surface fluxes that accounts for 70% and the entrainment flux, i. e., warmer and dryer air that enters in the ABL from the free troposphere. These two forcing mechanisms critically depend on some mesoscale process as sea breeze or mountain drainage that frequently appear in the studied area (Barcelona area).

The purpose of the present study is to study the sensitivity of the non-hydrostatic *Fifth-Generation PSU/NCAR Mesoscale Model (MM5)* from the Pennsylvania State University and U.S. National Center of Atmospheric Research (Dudhia, 1993; Grell and Stauffer, 1994) to describe accurately the evolution of the ABL in an urban area with complex orography. This model is usually used as one of the meteorological pre-processors for AQMs (Seaman, 2000; Hogrefe et al., 2001). Specifically, we study two physical parameterizations for the boundary layer. The intercomparisons between the lidar observations and the numerical results show that the modeled boundary layer strongly depends on the selected parameterization.

2 Description of the studied area

Barcelona is located on the West Mediterranean coast. The orography of the region is dominated by four main features: (1) the coastal plain which includes most of the cities in the Barcelona area, (2) the coastal mountain range with altitudes between 250 and 512 m; (3) the pre-coastal mountain range; and (4) two river valleys that frame the city and as we will show play an important role in the establishment of air-flow patterns. Apart from the complex orography, in the area there exists a great variety of types of soil: urban, forest, crops. This fact has great importance in the calculation of the surface fluxes by the model. The study models a region (smallest domain) covering an area of 31×31 km^2, see Fig. 1.

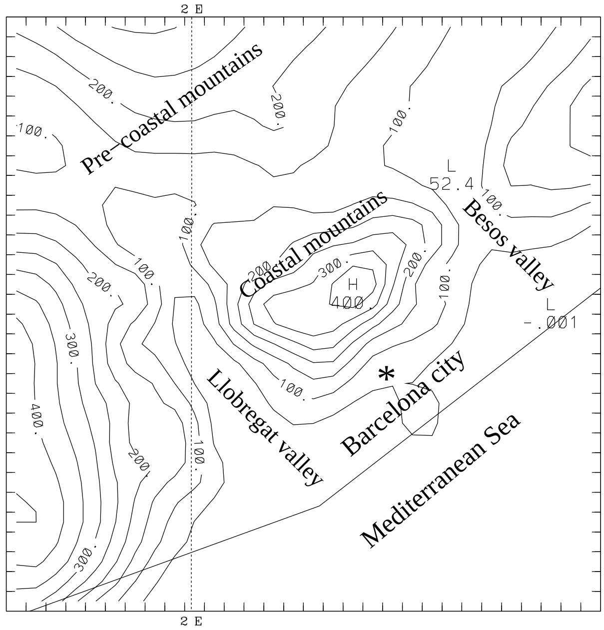

Fig. 1. The Barcelona geographical area. The asterisk marks approximately the lidar position.

3 Observations and numerical simulation setup

3.1 Lidar observations

In-situ observations are continuously monitored by means of radiosondes observations twice a day (0 and 12 UTC, UTC=LT-2) from the University of Barcelona. In addition, the boundary layer depth was measured by a 1064-nm elastic-backscatter lidar located at the Technical University of Catalonia (1 km apart from the radiosonde location). For one of the days presented in this study (17 July 2000), the cloud presence did not favor the estimation of the boundary layer depth (z_i) from the lidar data. It is important to notice that, to estimate z_i from the lidar data we have not use any algorithm. Following Cohn and Angevin (2000), we have only considered lidar data between 10 and 17 LT in order to avoid the appearance of the residual layer. In these conditions, it is possible to extract z_i from the maximum of the range-corrected backscatter signal received by the lidar.

3.2 Description of the numerical experiment

A numerical experiment is set up to investigate whether the non-hydrostatic mesoscale model MM5 (Dudhia, 1993; Grell and Stauffer, 1994) is able to reproduce the synoptic conditions of two different days (17 July and 16 October 2000) in the Barcelona area and, more specifically, to describe suitable, compared to lidar observations, the evolution of z_i in this area. Four domains, two-way nested, with 31 points each one, are defined using the following resolution: 27, 9, 3 and 1 km. The smallest domain is centered at the lidar position. The initial and boundary conditions are updated every six hours with information obtained from the the $0.5° \times 0.5°$ ECMWF model. In the vertical direction we have defined 26 σ-levels with high resolution in the ABL, 14 levels, approximately 100 m of grid spacing. Due to the complex orography and different land-use types that exist in the Barcelona area, for the two inner domains we use a topography and land-use data base with a 30" resolution. For the two outer domains the horizontal resolution is 1'.

The same physical descriptions, except for the planetary boundary layer (PBL) parameterizations, are prescribed for all the simulations. We use simple-ice for the explicit moisture scheme, cloud radiation for the radiation scheme, and Kain-Fritsch scheme for the cumulus parameterization. For the PBL parameterization, we use two different schemes. In the first simulation, the boundary layer processes are calculated using the *Medium Range Forecast* (MRF) scheme. This is a non-local, first-order closure PBL scheme based on Troen and Mahrt (1986) and developed by Hong and Pan (1996) as it is implemented in NCEP's Medium-Range Forecast Model. It consists in two regimes: a stable one and a free convection regime. The free convection regime takes into account the contributions from large-scale eddies in the local, vertical mixing-process throughout the whole PBL, introducing, in this way, the effect of the entrainment at the top of the boundary layer. In this scheme the turbulent fluxes are calculated as a function of friction velocity, convective velocity and height of the mixing layer. The MRF parameterization introduces a modified equation to calculate the boundary layer depth from the Richardson number. For the second case, we use the local *Eta-Mellor-Yamada* scheme. This scheme is a modified version of the boundary layer parameterization in NCEP's Eta-model, which is derived from the one employed in the Step-Mountain η-Coordinate Model of the U.S. National Meteorological Center (Janjić, 1994). In this scheme the turbulent fluxes are solved as a function of the exchange coefficients which depend on the turbulent kinetic energy and a master length scale, i., e., the 2.5 order Mellor-Yamada scheme (Mellor and Yamada, 1974). This scheme does not provided the depth of the boundary layer as direct output and this variable has to be obtained by additional calculations from the vertical profiles by means of the critical Richardson number.

As we have commented before, both parameterizations are widely used as a pre-processor for AQMs. Because we are interested in analyzing the parameterizations of the boundary layer, we decide not to use the model option to nudge surface and radiosonde observations during the simulations. The soil parameterizations used have differences with regard to the drag, heat and moisture coefficients and in the degree to which roughness length depends on surface wind speed. We use a ground temperature scheme which calculate soil temperature at six different levels using the diffusion equation. Finally, the model surface properties (albedo, roughness length, moisture availability and heat capacity) are specified 24 USGS land-use categories.

4 Results

4.1 17 July 2000

The synoptic situation for this day was characterized by a low-level pressure system located at the Atlantic coast of Iberian Peninsula which yield south-southeasterly winds at the studied area. In Fig. 2 the surface pressure at 12 UTC provided by the Catalan meteorological service (SMC) (left) and obtained with the model with the MRF parameterization in a expanded domain (right) is shown. As can be observed, the model reproduce quite well the synoptic situation. The same result is obtained with the ETA parameterization (not shown here).

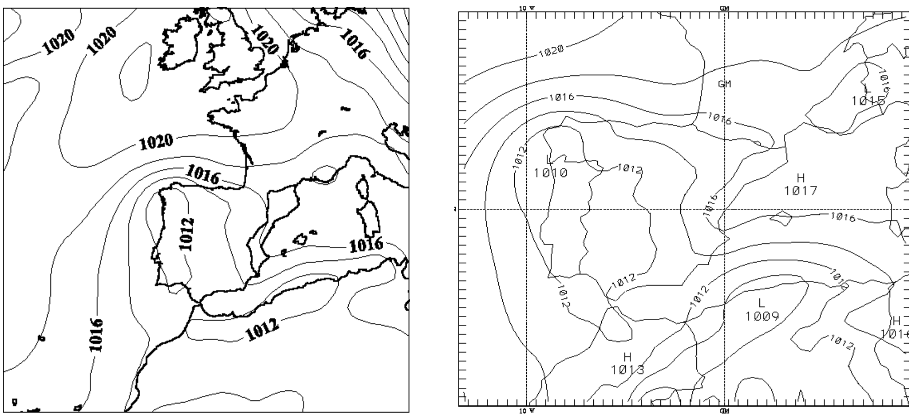

Fig. 2. Sea level pressure at 12 UTC of 17 July 2000. The values provided by the Catalan meteorological service (left) and by the model (right) are shown.

One of most frequently and observed phenomena in coastal areas is the sea breeze. In the Barcelona area this phenomena has great importance in summer days for cleaning of pollutants the domain advecting these pollutants to the rural areas (Beneito et al., 2002). On the other hand, sea breeze (or mountain drainage) can vary the boundary layer evolution. It is therefore necessary that the model suitably simulates these two phenomena. In Fig. 3 the wind field obtained with the model (MRF) at two different times on 17 June 2000 is shown. At 12 UTC (right), we can observe the see breeze entrance on the whole domain. At 3 UTC (left), it is clear the main role played by orography, conducting the mountain drainage through the valleys. Similar results are found with ETA parameterizations (not shown here).

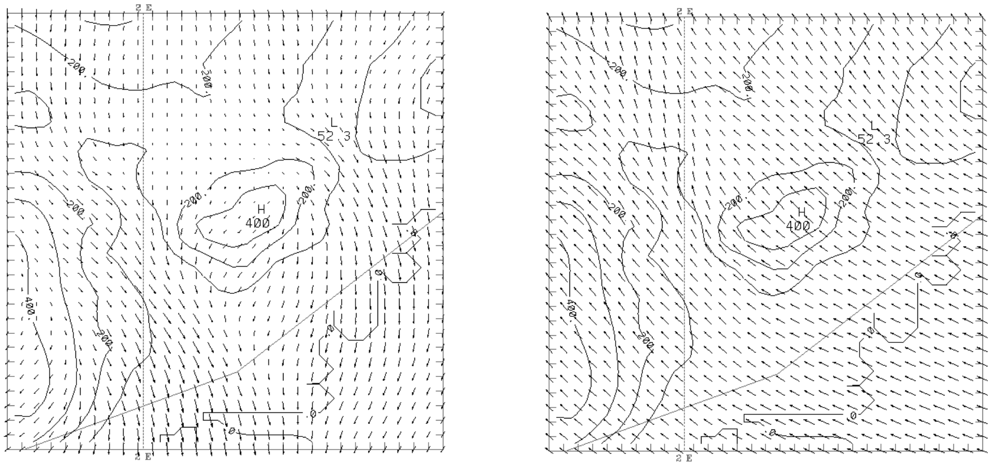

Fig. 3. Wind field on the smallest domain of the simulation with MRF parameterization at 3 UTC (left) and 12 UTC (right).

Fig. 4 depicts a comparison of the vertical profile of the potential temperature and specific humidity at 12 UTC from radiosondes and from the MM5 with each of the studied parameterizations. The observed vertical profile shows a well mixed layer capped with a strong and sharp inversion. From the comparison, it is clear that the model provides lower entrainment rates no matter the parameterization is considered. Because of that, the simulated convective boundary layer is colder and wetter. Observing the two parameterizations, MRF provides results which agree better with the observations. Similar results were found by Braun and Tao (2000) and Vilà-Guerau de Arellano et al. (2002) who studied the MM5 PBL-parameterizations on the development of a hurricane and in a rural area, respectively. As it was commented in section 1, the entrainment of warm air from above is one of the key mechanisms for the development of the convective boundary layer. For this reason, it is interesting to compare the evolution of z_i obtained by the model with the observations. In Fig. 5, z_i provided by the model with MRF parameterization is shown. As can be observed, the model provides a typical evolution of z_i for a summer day in the Barcelona area. Moreover, the simulated boundary layer is in close agreement with the lidar observations and with the boundary layer height estimated from the radiosonde at 12 UTC. Unfortunately, clouds appear this day over the lidar area and it was not possible to obtain more unaffecteted lidar data and, on the other hand, due to the low entrainment rates (see Fig. 4) it was not possible to obtain z_i from the vertical profiles in the ETA case.

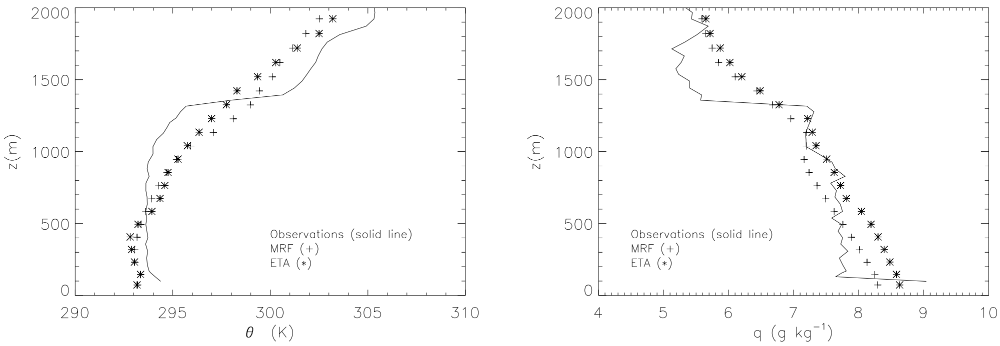

Fig. 4. Vertical profile of the potential temperature (left) and specific humidity (right) observed by the radiosonde (solid line) and obtained with the model with MRF (crosses) and ETA (asterisks) PBL parameterizations.

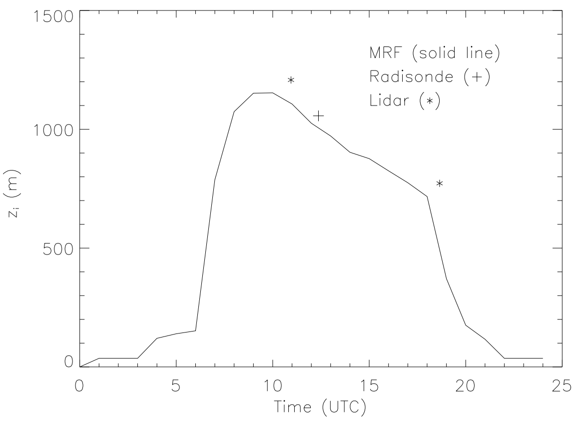

Fig. 5. A comparison of the boundary layer depth during 17 July 2000 observed by the lidar (asterisk), by the radiosonde (cross) and calculated with the model (solid line). For the radiosonde the observed z_i is estimated at the height where the potential temperature equals the temperature of the boundary layer plus 1 K.

4.2 16 October 2000

The synoptic situation was dominated by a high-level pressure system located at the Atlantic Ocean, west of the Iberian Peninsula which produces north-westerly light winds at the Barcelona area. In spite of the cumulus presence during great part of the day they did not affect to the lidar observations.

For this day, the same numerical experiment is performed. Fig. 6 shows z_i from the lidar observations and obtained with the two parameterization of the model. In this case, for the two parameterizations we estimate the boundary layer depth by calculating from the vertical profile the Richardson number and using a threshold critical value ($Ri_c = 0.5$). The MRF parameterization models the growth of the boundary layer much better than the ETA, giving a similar value for the maximum of z_i. ETA clearly underestimates the depth of the boundary layer during the whole day, but the maximum value of z_i happens at the same time than the lidar data. On the contrary, MRF parameterization reach its maximum 1 hour after the observations. From that result, it seems clear that the parameterization which solves the TKE as a prognostic equation to calculate the turbulent fluxes (ETA), gives turbulent motions that are not strong enough to model a well developed CBL.

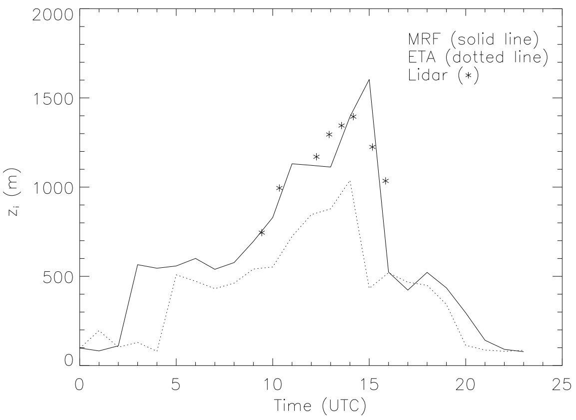

Fig. 6. Same as Fig. 5 for 16 October 2000. For this day there was not radiosonde data available.

5 Conclusions

The development of two convective boundary layer in an urban area has been simulated by means of MM5. Two boundary layer parameterizations largely used in weather forecast models has been used. Both schemes simulate a colder and wetter ABL compared with the observations and largely underestimates the observed entrainment rates. However, the MRF parameterization simulates quite well the boundary growth, giving similar values for the maximum height of the boundary layer. The ETA parameterization clearly underestimates the boundary layer depth for 16 October.

References

Beneito, J., Soler, M. R., Alarcón, M., Pino, D., 2002. Modelling horizontal concentration of ozone within medium latitude urban areas. In: 26th General Assembly of the Europen Geophysical Society.

Braun, S. A., Tao, W. K., 2000. Sensitivity of high-resolution simulations of hurricane Bob (1991) to planetary boundary layer parameterizations. Mon. Wea. Rev. 128, 3941–3961.

Cohn, S. A., Angevin, W. M., 2000. Boundary layer height entrainment zone thickness measured by lidars and wind-profiling radars. J. Appl. Meteorol. 39, 1233–1247.

Dudhia, J., 1993. A nonhydrostatic version of the Penn-State NCAR mesoscale model: Validation tests and simulation of an Atlantic cyclone and cold front. Mon. Wea. Rev. 121, 1593–1513.

Grell, G. A., Stauffer, D. R., 1994. A description of the fifth generation Penn State/NCAR mesoscale model (MM5). Tech. Rep. NCAR-TN-398+STR, National Center for Atmospheric Research, Boulder, CO, 138 pp.

Hogrefe, C., Rao, S. T., Kasibhatla, P., Kallos, G., Tremback, C. J., Hao, W., Olerud, D., Xiu, A., McHenry, J., Alapaty, K., 2001. Evaluating the performance of regional-scale photochemical modeling systems: Part I – meteorological predictions. Atmos. Env. 35, 4159–4174.

Hong, S. Y., Pan, H. L., 1996. Nonlocal boundary layer vertical diffusion in a medium-range forecast model. Mon. Wea. Rev. 124, 2322–2339.

Janjić, Z. I., 1994. The step-mountain eta corrdinate model: further developments of the convection, viscous sublayer, and turbulence closure schemes. Mon. Wea. Rev. 122, 927–945.

Mellor, G. L., Yamada, T., 1974. A hierarchy of turbulence closure models for planetary boundar layer. J. Atmos. Sci. 31, 1791–1806.

Seaman, N. L., 2000. Meteorological modeling for air-quality assessments. Atmos. Env. 34, 2231–2259.

Troen, I., Mahrt, L., 1986. A simple model of the atmospheric boundary layer; sensitivity to surface evaporation. Bound.-Layer Meteor. 37, 129–148.

Vilà-Guerau de Arellano, J., Duynkerke, P. G., Pino, D., 2002. Entrainment process in mesoscale models: observational validation. In: Sportisse, B. (Ed.), Air Pollution Modelling and Simulation. Springer, pp. 13–20.